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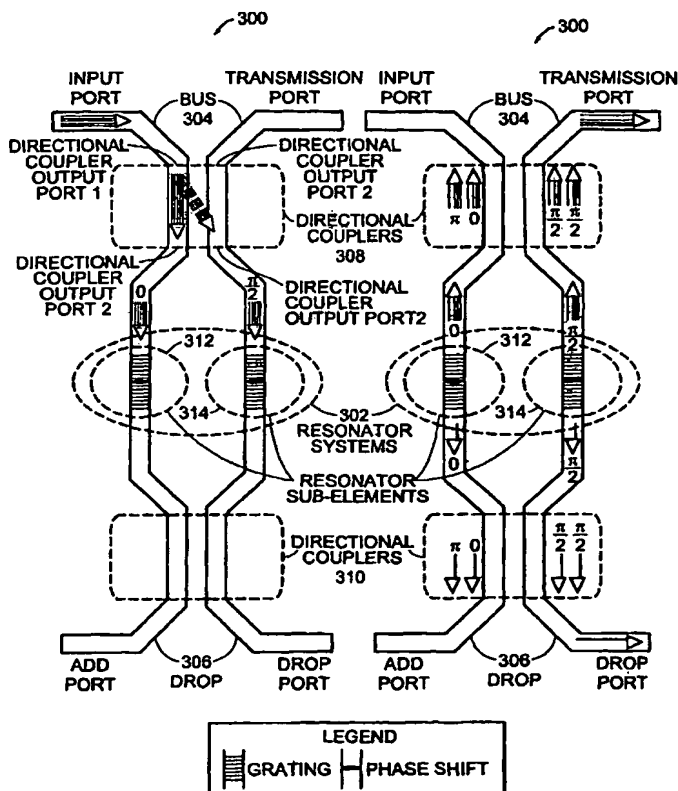
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(54) Title: RESONATOR ASSISTED MACH-ZEHNDER INTERFEROMETER ADD/DROP FILTER



(57) Abstract: An electromagnetic field frequency filter (300) which includes a bus waveguide (304) that carries a signal having a plurality of frequencies, including a desired frequency, and a drop waveguide.(306) A resonator-system (302) is coupled to the bus and drop waveguides via directional couplers (308, 310) and transfers the desired frequency from the bus waveguide (304) to the drop waveguide (306) while allowing transmission of the remaining frequencies in the bus waveguide.(304) The input signal in the bus waveguide (304) is coupled from the bus waveguide (304) to the resonator-system (302) by a first directional coupler.(308) The resonator-system (302) includes two sub-elements (312, 314) each comprising at least one resonator. The first directional coupler (308) splits the input signal into two preferably equal parts and directs each part into a resonator sub-element.(312, 314). The desired frequency is transferred to the drop waveguide (306) by a second directional coupler.(310) The non-desired frequencies are returned to the bus waveguide,(304) in the forward direction, by the directional coupler (308). Preferably, the resonators are formed by periodic dielectric structures with phase shifts.

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## RESONATOR ASSISTED MACH-ZEHNDER INTERFEROMETER ADD/DROP FILTER

**PRIORITY INFORMATION**

5           This application claims priority from U.S. patent application Ser. No. 10/096,616 filed on March 7, 2002, which is incorporated herein by reference in its entirety.

          U.S. patent application Ser. No. 10/096,616 is a continuation-in-part application of Ser. No. 09/619,926 filed July 20, 2000, which is a continuation of Ser. No. 10 09/080,037 filed May 15, 1998, now U.S. Pat. No. 6,101,300, which is a continuation-in-part of Ser. No. 08/968,314 filed November 12, 1997, now U.S. Pat. No. 6,130,969, which is a continuation-in-part of Ser. No. 08/871,747 filed June 9, 1997, now abandoned.

**BACKGROUND OF THE INVENTION**

15           In modern DWDM systems, it is essential to have devices that can add and drop signals to and from a stream of signals. In U.S. Pat. No. 6,101,300, a bus waveguide and a drop waveguide are coupled to a resonator-system. At the resonant frequency of the resonator-system, a desired signal can be completely transferred from the bus waveguide to the drop waveguide. Higher order filters are realized by increasing the 20 number of resonators. U.S. Pat. No. 6,101,300 also describes various switching mechanisms for providing on/off switching and modulation.

**SUMMARY OF THE INVENTION**

25           In accordance with exemplary embodiments of the invention, there is provided an add/drop filter that employs directional couplers to couple the resonator-system to the waveguides. The directional-coupler assisted (DCA) add/drop filter is another exemplary embodiment of the invention in which the resonator-system is coupled to the bus and drop waveguides via directional couplers. One advantage of this embodiment 30 is improved tolerance to parameter variations.

          In another exemplary embodiment of the invention there is provided an electromagnetic field frequency filter that includes a bus waveguide that carries a signal having a plurality of frequencies, including a desired frequency, and a drop waveguide.

A resonator-system is coupled to the bus and drop waveguides via directional couplers and transfers the desired frequency from the bus waveguide to the drop waveguide while allowing transmission of the remaining frequencies in the bus waveguide. The input signal in the bus waveguide is coupled from the bus waveguide to the resonator-system by a first directional coupler. The resonator-system includes two sub-elements each comprising at least one resonator. The first directional coupler splits the input signal into two preferably equal parts and directs each part into a resonator sub-element. The desired frequency is transferred to the drop waveguide by a second directional coupler. The non-desired frequencies are returned to the bus waveguide, in the forward direction, by the first directional coupler.

Various types of resonators can be used in the DCA filter, such as photonic-crystal resonators (including grating-based resonators), in-line resonators, and side-coupled resonators. The resonator sub-elements can themselves be composed of sub-elements in a hierarchal manner, as described in the parent case. The number of resonators can be modified to obtain a desired filter lineshape.

The DCA filter can be switched using electrical, optical, thermal or mechanical means to induce absorption, index variation, or frequency tuning, as described in the parent case. In another exemplary embodiment, an eight-resonator filter is switched off by tuning the resonant frequencies of the resonators to an adjacent unused frequency slot so that the filter does not drop the signal at the desired frequency.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a schematic block diagram of a side-coupled filter in accordance with the invention;

FIG. 2 is a schematic block diagram of a DCA filter in accordance with the invention;

FIG. 3 is a schematic diagram of an exemplary embodiment of a DCA filter;

FIG. 4 is a graph showing a filter response of an exemplary two-resonator DCA filter;

FIG. 5 is a schematic diagram of another exemplary embodiment of a DCA filter;

FIG. 6 is graph showing a filter response of an exemplary four-resonator DCA filter;

FIGs. 7A and 7B are schematic diagrams of two other exemplary embodiments of six-resonator and eight-resonator DCA filters, respectively;

FIG. 8 is a graph showing a filter response of an exemplary six-resonator DCA filter;

5 FIG. 9 is a graph showing a filter response of an exemplary eight-resonator DCA filter;

FIG. 10 is a schematic diagram of another exemplary embodiment of a DCA filter; and

10 FIG. 11 is a schematic diagram of another exemplary embodiment of a DCA filter.

### **DETAILED DESCRIPTION OF THE INVENTION**

FIG. 1 is a schematic block diagram of a side-coupled add/drop filter 100 in accordance with the invention. The add/drop filter includes a resonator-system 102, which supports at least two resonant modes, coupled to a bus waveguide 104 and a drop waveguide 106. The resonator-system 102 includes one or more resonators that, in addition to being coupled to the waveguides, can also be coupled among themselves. Coupling between the various resonator modes is configured to cancel reflection in the input port. On/off switching and modulation is also provided using a variety of switching mechanisms.

20 In accordance with the invention, alternative geometries of this add/drop filter using directional couplers to couple the resonator-system to the waveguides are provided. FIG. 2 is a schematic block diagram of a DCA add/drop filter 200 in accordance with the invention. The DCA add/drop filter 200 includes a bus waveguide 204 that is coupled to a resonator-system 202 via a first directional coupler 208, and a drop waveguide 206 is coupled to the resonator-system via a second directional coupler 210. At the desired frequency, the signal inside the bus waveguide excites the resonator modes of the resonator-system. Coupling between the various resonator modes cancel reflection in the input port. In turn, the desired frequency is coupled into the drop waveguide. The resonator-system modes are designed to provide the desired spectral response for the drop port.

30 The resonator-system in the DCA embodiment supports at least two localized resonant modes coupled to the bus and drop waveguides. At least two of the modes

have substantially the same frequency and the same quality factor. In both the side-coupled and DCA embodiments, shown in FIGs. 1 and 2, respectively, the desired frequency inside the bus excites at least two resonant modes of the resonator-system. In the side-coupled embodiment, the bus and drop waveguides are side-coupled directly to the resonator-system and in the DCA embodiment the bus and drop waveguides are coupled to the resonator-system by directional couplers.

The configuration of the DCA embodiment is mathematically equivalent to the side-coupled embodiment; there is a one-to-one mapping between them. Moreover, in both filter configurations, the signal in the drop waveguide can be made to propagate in either the forward or backward direction by changing the relative phase of the modes in the resonator-system.

The use of directional couplers has the highly-desired effect of reducing the sensitivity of the filter to parameter variations. Hence, an advantage of the DCA configuration is that it is more tolerant to parameter variations that occur during fabrication. As a result, the backward reflection in both the input and drop ports is minimized for a large range of parameter variations.

In an exemplary embodiment of the invention as shown in FIG. 3, a DCA add/drop filter 300 includes a resonator-system 302 coupled to bus 304 and drop 306 waveguides. The resonator-system 302 is divided into two identical grating resonator sub-elements 312, 314. The DCA filter reflection and lineshape can be independently adjusted by adjusting the parameters of two directional couplers 308, 310 and the parameters of the resonator-system, respectively. The two arms of the resonator-system preferably have the same decay rate and the same frequency.

The directional couplers split the input signal into the two arms of the resonator-system, and also recombine the signals from the two arms either into the bus or drop waveguide. The recombined signals are directed preferably in the forward direction; the desired frequency propagates into the drop waveguide while the non-desired frequencies propagate along the bus waveguide. The directional couplers are preferably 50/50 splitters or combiners so that the bus signal is equally split between the two resonator sub-elements.

In this embodiment, the input signal enters the first input port of the first directional coupler 308 and is equally split into the two output ports of the directional coupler. The second output port has a  $\frac{\pi}{2}$  phase difference relative to the first output

port of the directional coupler. The directional coupler output ports are connected to the two resonator sub-elements 312, 314. The non-resonant frequencies of the input signal are reflected by the resonator sub-elements back into the two output ports of the directional coupler. The directional coupler recombines the reflected signals into the second input port of the directional coupler, which transmits the recombined signal into the bus waveguide in the forward direction. The reflected signals in the first input port recombine destructively and produce no reflection in the input port of the bus waveguide.

The desired frequency of the input signal is transmitted through the resonator sub-elements, recombined by the second directional coupler 310, and then transmitted into the drop waveguide 306. The DCA filter response for this embodiment is shown in FIG. 4.

From symmetry, a desired frequency introduced into the add port of the drop waveguide 306 would be transferred to the bus waveguide 304. Also, a desired frequency introduced into the transmission port of the bus waveguide would be transferred to the drop waveguide.

Direct coupling between the resonators in each resonator sub-element provides a means to achieve high-order filter functions. By increasing the number of resonators in each resonator sub-element, the lineshape of the resonator-system can be made steeper and flatter. FIG. 5 is a schematic diagram of another exemplary embodiment of a DCA add/drop filter 500 of the invention. The filter 500 includes four resonators (516, 518, 520, 522), two located in each of two resonator sub-elements 512, 514. Each resonator supports a single mode. The two resonator sub-elements are preferably spatially separated from each other to prevent direct coupling between them. Each resonator sub-element supports a sub-element mode consisting in part of a linear combination of the resonant modes of the resonator sub-elements. Coupling between the various resonator modes is specifically configured to cancel reflection in the input port. The two sub-element modes are specifically configured to have the same frequency profiles. FIG. 6 is a graph showing the frequency response of the DCA embodiment with four resonators shown in FIG. 5.

Since the non-desired frequencies are reflected by the gratings, the gratings preferably have large grating strengths so that the stop band covers the entire range of interest.

FIGs. 7A and 7B are schematic diagrams of exemplary embodiments of two DCA filters 700 and 750. The filters 700 and 750 are examples of six- and eight-resonator embodiments with two resonator sub-elements each containing three and four resonators, respectively. FIGs. 8 and 9 are graphs showing the frequency responses of the exemplary embodiments with six and eight resonators shown in FIGs. 7A and 7B, respectively. The filter lineshape becomes flatter and sharper with increasing number of resonators, as expected.

FIG. 10 is a schematic diagram of an exemplary embodiment of an eight-resonator DCA filter 1000 with two resonator sub-elements each containing four side-coupled resonators. The number of resonators can be extended to any desired value, although the physical layout and available space for the resonators may limit the number of resonators.

The resonator sub-elements can support any type of resonator, such as photonic-crystal resonators (including grating-based resonators), in-line resonators, side-coupled resonators, ring-coupled gratings, and ring resonators. Gratings are a class of photonic crystals. Photonic crystals (also known as photonic bandgap materials) are defined as composite materials with a one-dimensional, two-dimensional, or three-dimensional spatial periodic variation of electromagnetic properties such as index of refraction. FIGs. 10, and 11 show two exemplary side-coupled resonator embodiments of the invention. FIG. 11 is a schematic diagram of another exemplary embodiment of a DCA filter 1100. In the embodiment shown in FIG. 11, preferably broadband reflective elements are used to reflect the non-desired frequencies. Examples of broadband reflective elements include but are not limited to waveguide gratings and 90° waveguide terminations.

The DCA resonator-system has preferably two or more resonator sub-elements. The number of resonator sub-elements can be extended to any desired value. Each subsequent sub-element can further be subdivided in a hierarchical fashion.

All of the previously discussed embodiments can be switched using the previously mentioned switching mechanisms. For example, in a further specific embodiment of the invention, the eight-resonator DCA filter 750 of FIG. 7B is switched using a heating mechanism such as a resistive heater located above the resonator-system. When the resonator-system transfers the desired frequency to the drop waveguide, the DCA filter is in the cross state. By activating the resistive heater

above the resonator-system, the resonant frequency of the resonator-system can be tuned away from the desired frequency to a vacant frequency slot, hence the desired frequency is no longer transmitted to the drop waveguide and the DCA filter is in the bar state. Other switching mechanisms described in the parent case can also be applied to the DCA filter. For example, the resonances of the resonator-system can be spoiled by absorption, thereby eliminating the drop signal.

Although the invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is:



## CLAIMS

1           1. An electromagnetic field frequency filter comprising:  
2           an input waveguide which carries a signal having at least one frequency  
3           including at least one desired frequency;  
4           an output waveguide; and  
5           a resonator-system coupled to said input and output waveguides by at least one  
6           directional coupler, said resonator-system transfers said at least one desired frequency  
7           to said output waveguide, said resonator-system including at least two resonator sub-  
8           elements each supporting at least one mode at or near said desired frequency.

1           2. The filter of claim 1, wherein at least one of said resonator sub-element  
2   supports only one mode.

1           3. The filter of claim 1, wherein at least two of said modes have substantially  
2   the same energy dissipation rates.

1           4. The filter of claim 1, wherein each said resonator sub-element comprises at  
2   least one waveguide section, each waveguide section supporting at least one resonator.

1           5. The filter of claim 1, wherein each said resonator sub-element comprises at  
2   least two resonators each supporting only one mode.

6. The filter of claim 5, wherein said at least two resonators in at least one resonator sub-element support at least one resonator sub-element mode including a linear combination of the resonant modes of said resonator sub-element, said resonator-system being specifically configured such that said resonator sub-element mode has substantially the same frequency profile as the sub-element mode of at least one other resonator sub-element.

1           7. The filter of claim 1, wherein said resonator-system is specifically  
2 configured such that reflection of the desired frequency in the input port is cancelled.

1           8. The filter of claim 1, wherein each of said input and output waveguides is  
2   physically connected to at least one sub-element of said resonator-system by a  
3   waveguide.

1           9. The filter of claim 1, wherein said resonator-system comprises at least one  
2 periodic dielectric structure.

1           10. The filter of claim 9, wherein said periodic dielectric structure comprises at  
2 least one phase shift defining at least one resonator.

1           11. An electromagnetic field frequency filter comprising:  
2           an input waveguide which carries a signal having at least one frequency  
3 including at least one desired frequency;  
4           an output waveguide; and  
5           a resonator-system coupled to said input and output waveguides by at least one  
6 directional coupler, said resonator-system transfers said at least one desired frequency  
7 to said output waveguide, said resonator-system being comprised of at least two  
8 resonator sub-elements each supporting at least one mode at or near said desired  
9 frequency, said resonator sub-elements each comprising at least one periodic dielectric  
10 structure.

1           12. The filter of claim 11, wherein each of said input and output waveguides is  
2 physically connected to at least one sub-element of said resonator-system by a  
3 waveguide.

1           13. The filter of claim 11, wherein each said resonator sub-element comprises  
2 at least one waveguide section, each said waveguide section supporting at least one  
3 resonator.

1           14. The filter of claim 13, wherein each said resonator sub-element comprises  
2 at least two resonators, each supporting only one mode.

1           15. An electromagnetic field frequency filter comprising:  
2           an input waveguide which carries a signal having at least one frequency  
3 including at least one desired frequency;  
4           an output waveguide; and  
5           a resonator-system coupled to said input and output waveguides by at least one  
6 directional coupler, said resonator-system being operable for the adjustable transfer of  
7 said at least one desired frequency to said output waveguide in response to a variation

8 of the internal decaying rate or resonance frequency of at least one resonator of said  
9 resonator-system, said resonator-system including at least two resonator sub-elements  
10 each supporting at least one mode at or near said desired frequency when said transfer  
11 occurs substantially.

1 16. The filter of claim 15, wherein said resonator-system comprises at least one  
2 periodic dielectric structure with at least one phase shift defining at least one resonator.

1 17. The filter of claim 15, wherein said internal decaying rate or resonance  
2 frequency of said at least one resonator is varied by changing the absorption  
3 characteristics or index of refraction of said resonator-system.

1 18. The filter of claim 15, wherein said internal decaying rate or resonance  
2 frequency of said at least one resonator is varied by an electrical, thermal, optical, or  
3 mechanical means.

1 19. The filter of claim 15, wherein said input waveguide has an input port and  
2 an output port, said output waveguide has a forward port and a backward port, and said  
3 internal decaying rate or resonance frequency of said at least one resonator is varied to  
4 provide selective switching of said desired frequency into either the output port or the  
5 forward port.

1 20. The filter of claim 15, wherein said input waveguide has an input port and  
2 an output port, said output waveguide has a forward port and a backward port, and said  
3 internal decaying rate or resonance frequency of said at least one resonator is varied to  
4 provide selective splitting of said desired frequency into at least two of said four ports.

1 21. The filter of claim 15, wherein said at least two sub-element modes have  
2 substantially the same energy dissipation rates when said transfer occurs substantially.

1 22. An electromagnetic field frequency filter comprising:  
2 an input waveguide which carries a signal having at least one frequency  
3 including at least one desired frequency;  
4 an output waveguide; and  
5 a resonator-system coupled to said input and output waveguides by at least one  
6 directional coupler, said resonator-system being operable for the adjustable transfer of

7 said at least one desired frequency to said output waveguide in response to a variation  
8 of the index of refraction or the absorption in the vicinity of at least one resonator of  
9 said resonator-system.

1 23. The filter of claim 22, wherein said resonator-system is specifically  
2 configured such that reflection of the desired frequency in the input port is cancelled.

1 24. The filter of claim 22, wherein said resonator-system comprises at least one  
2 periodic dielectric structure with at least one phase shift defining at least one resonator.

1 25. The filter of claim 22, wherein the resonator-system comprises at least two  
2 resonator sub-elements, each supporting at least one mode at or near said desired  
3 frequency when said transfer occurs substantially.

1 26. The filter of claim 25, wherein each said resonator sub-element comprises  
2 at least two resonators, each supporting only one mode.

1 27. The filter of claim 25, wherein each said input and output waveguide is  
2 physically connected to at least one sub-element of said resonator-system by a  
3 waveguide.

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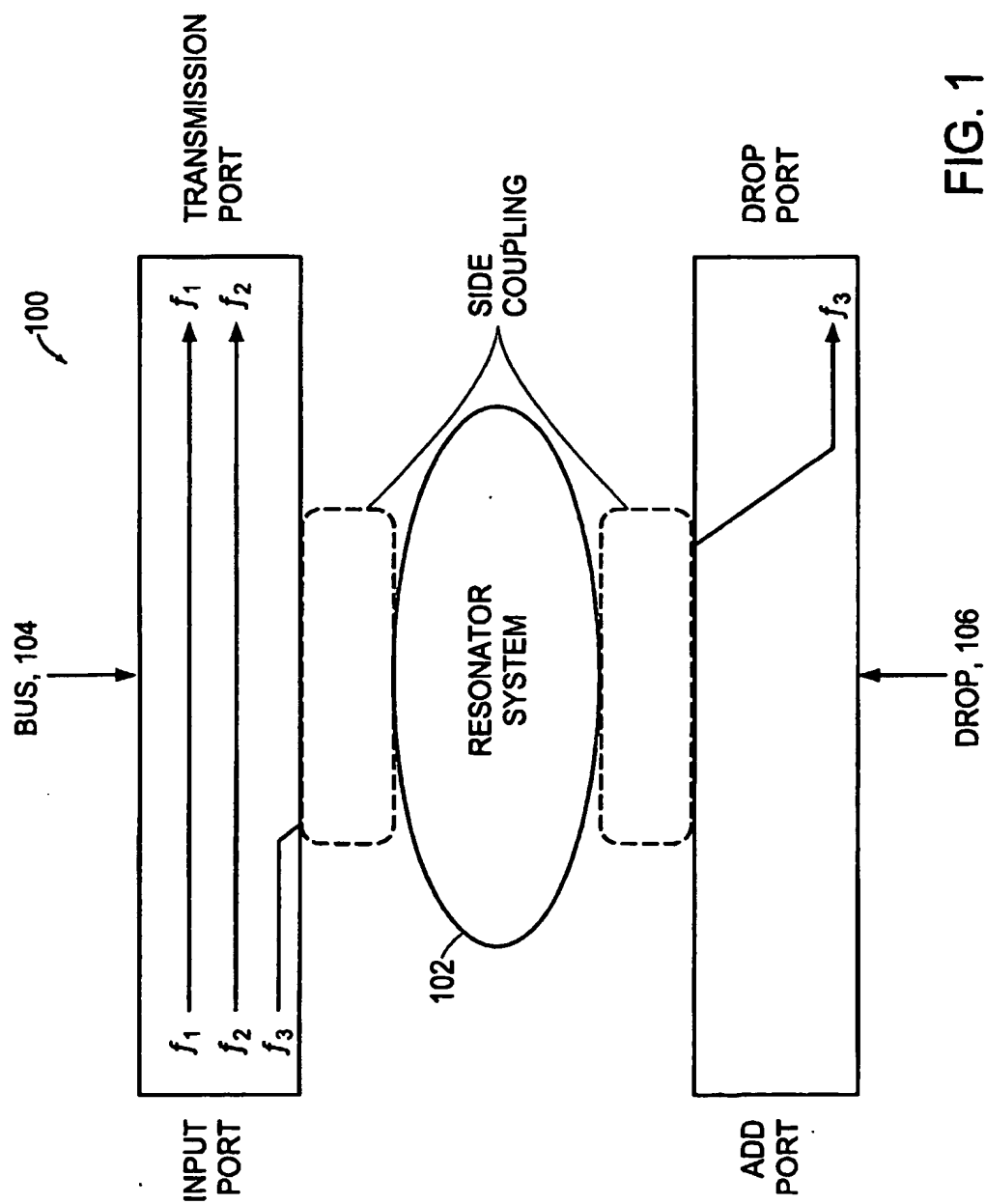


FIG. 1

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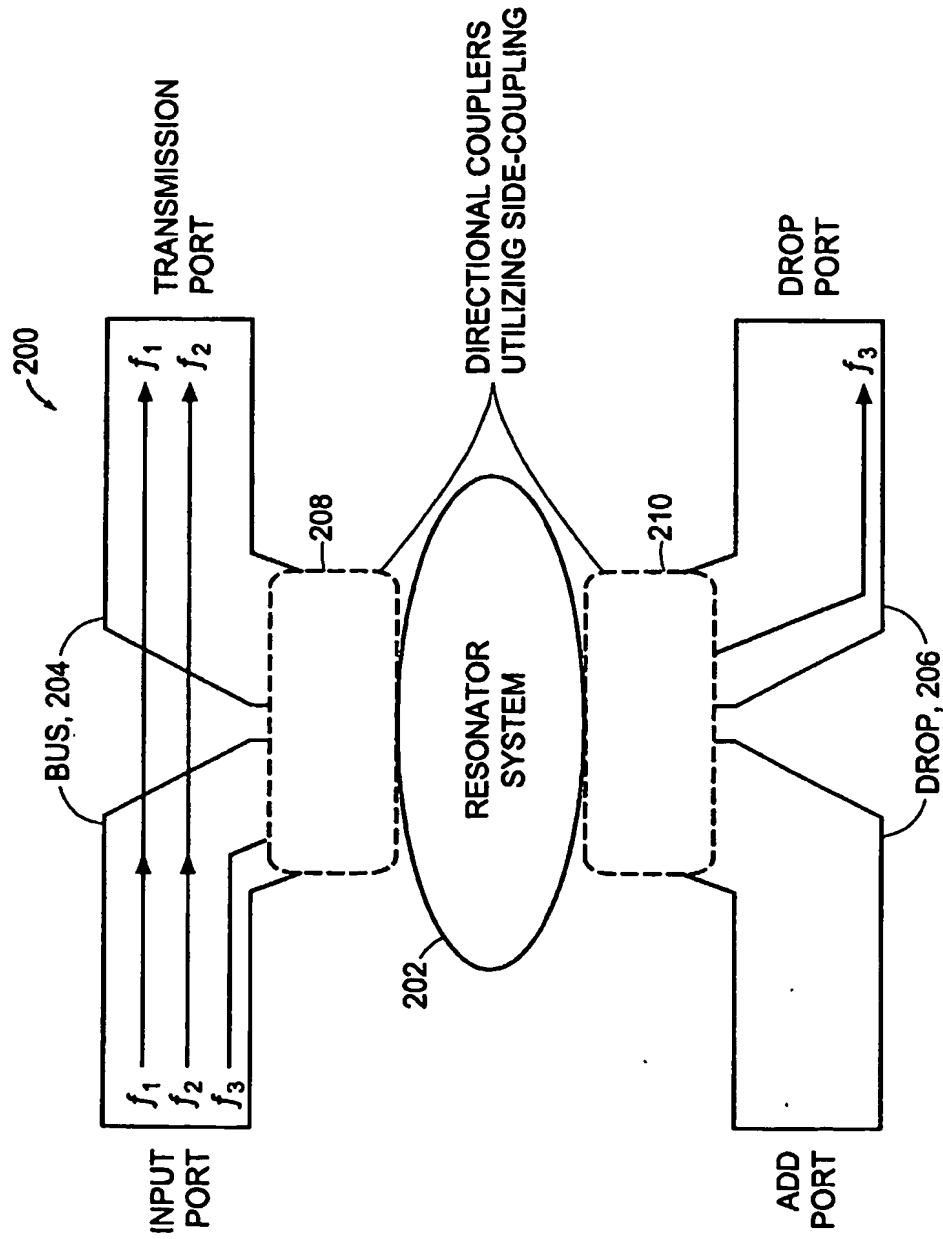


FIG. 2

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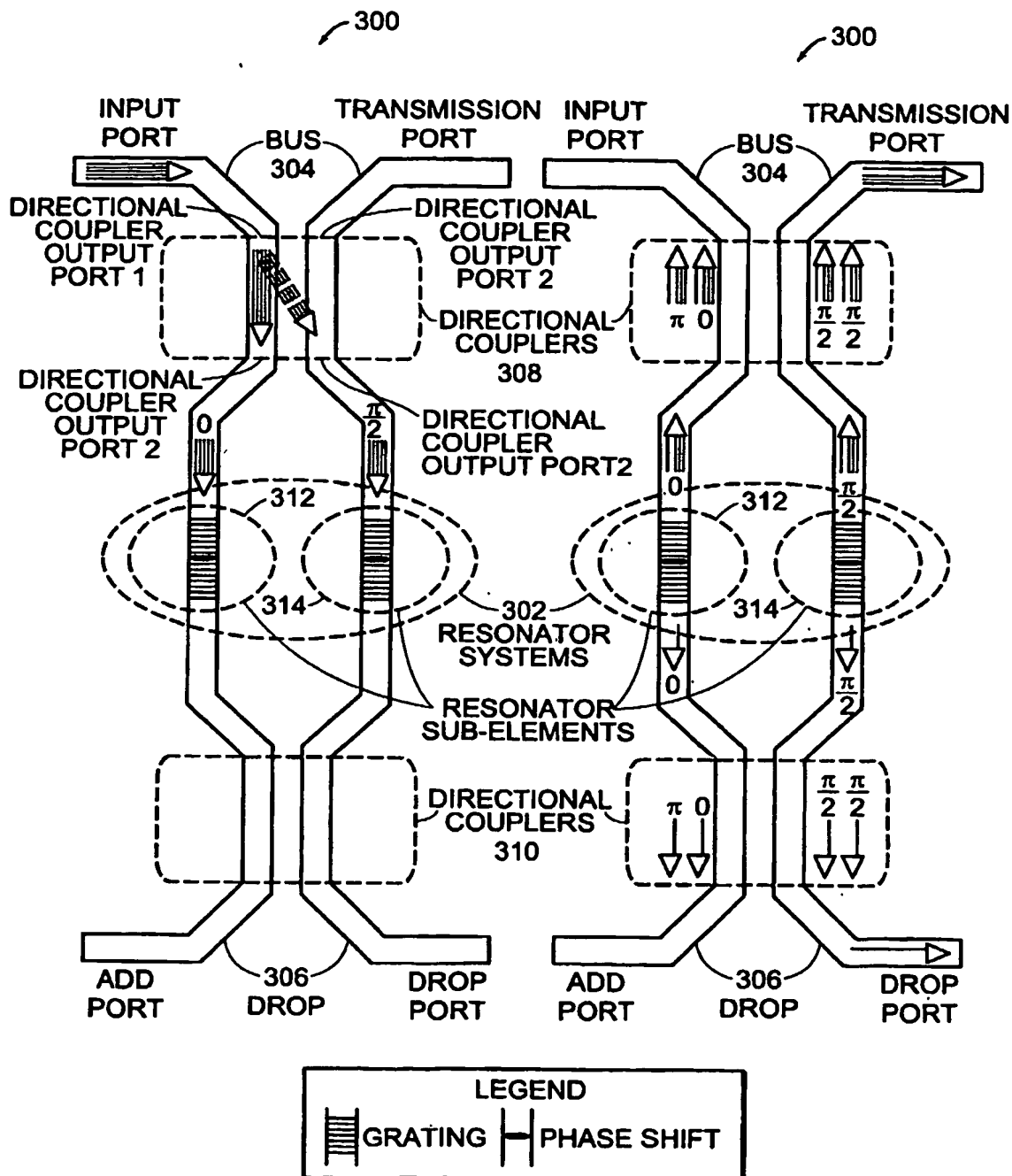


FIG. 3

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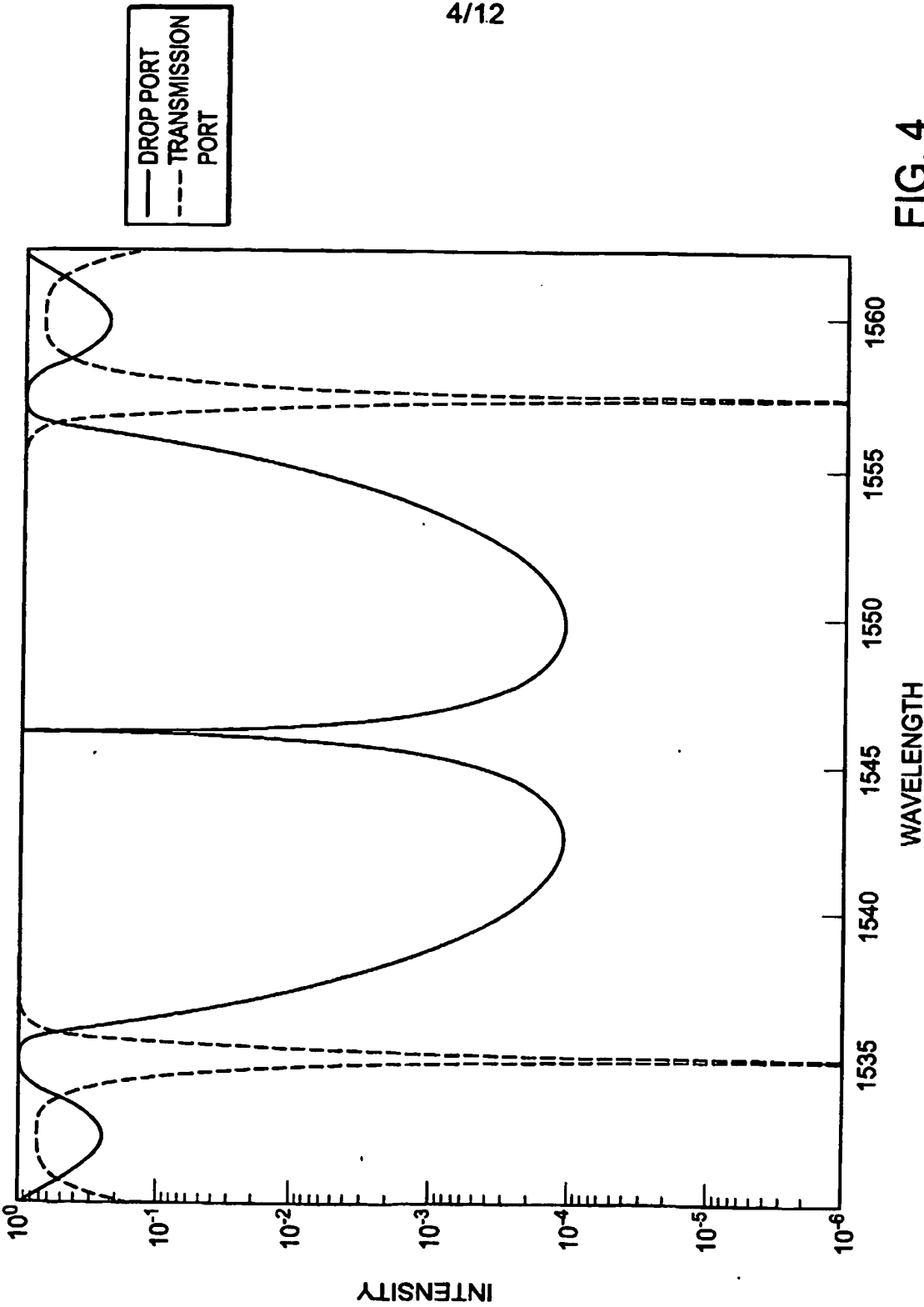


FIG. 4



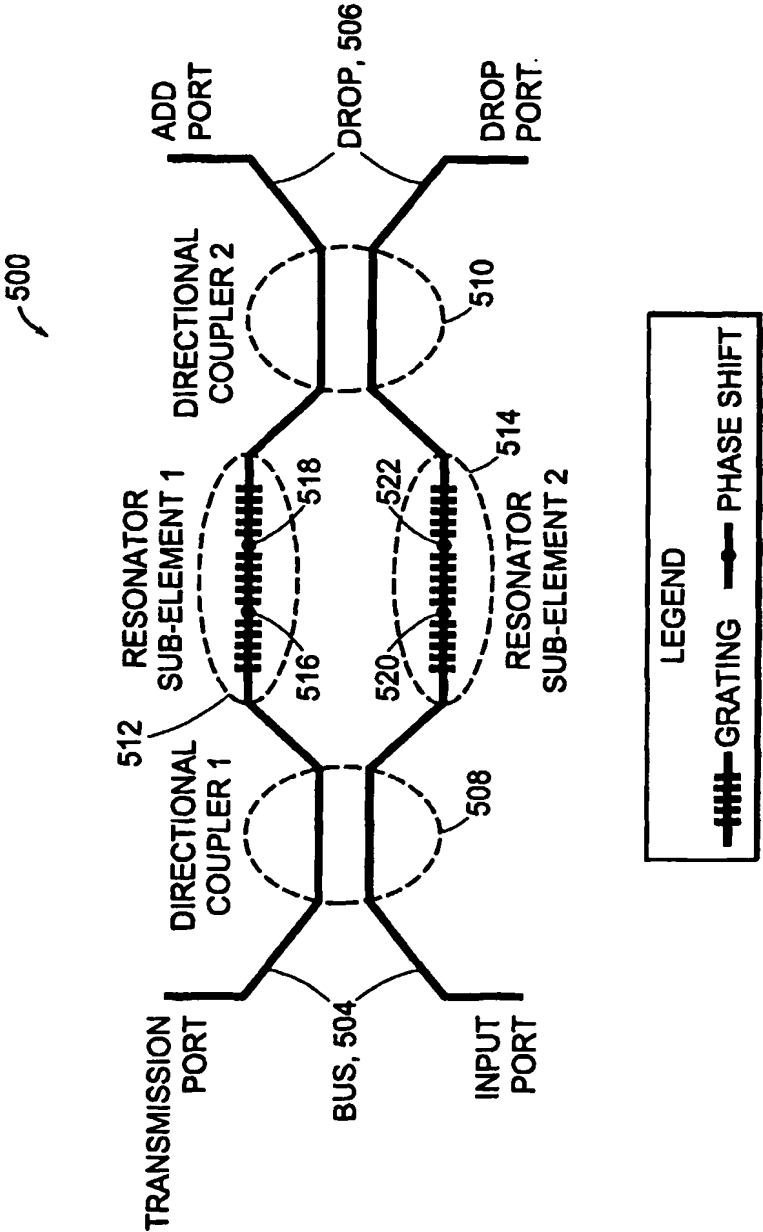


FIG. 5

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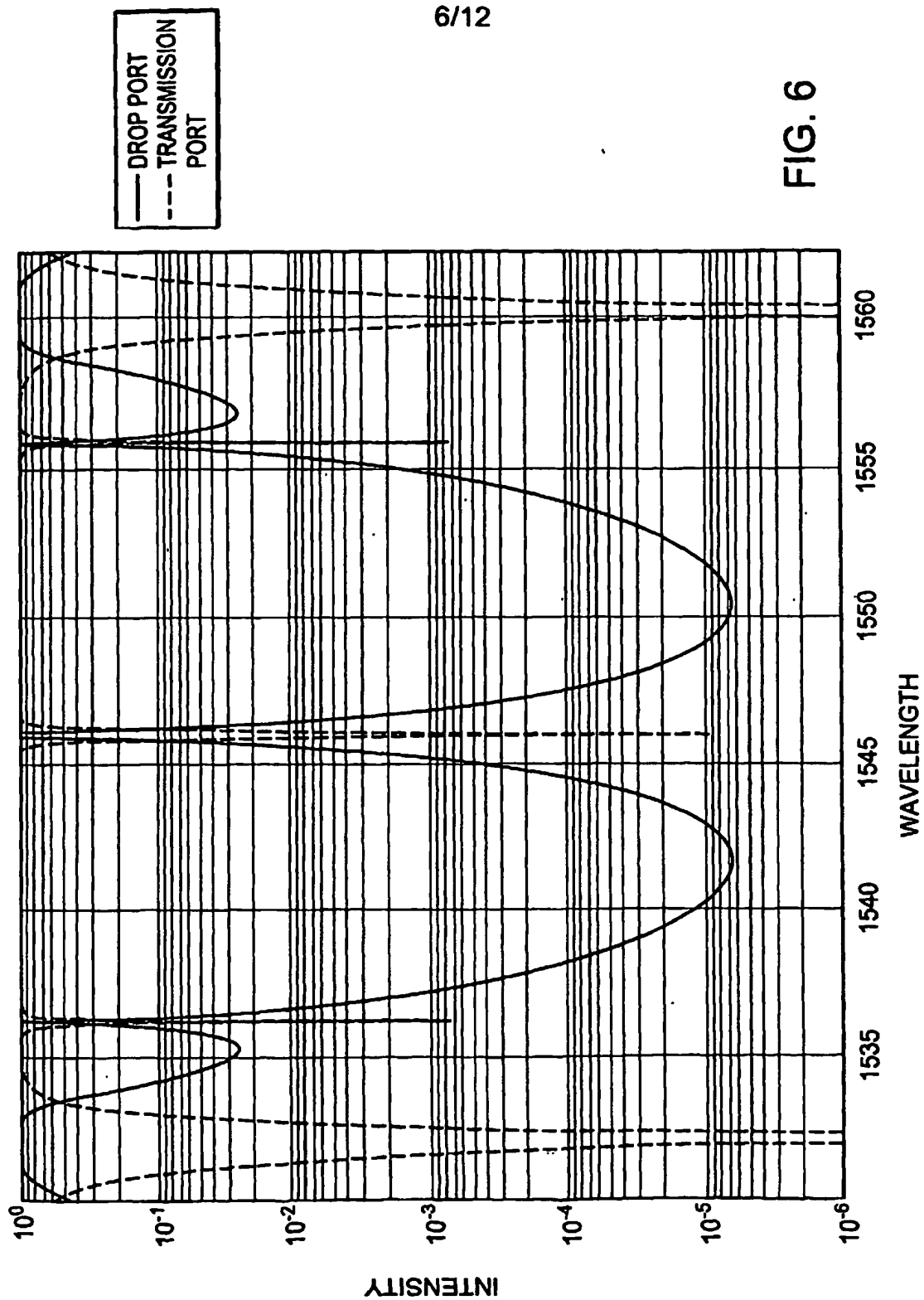


FIG. 6

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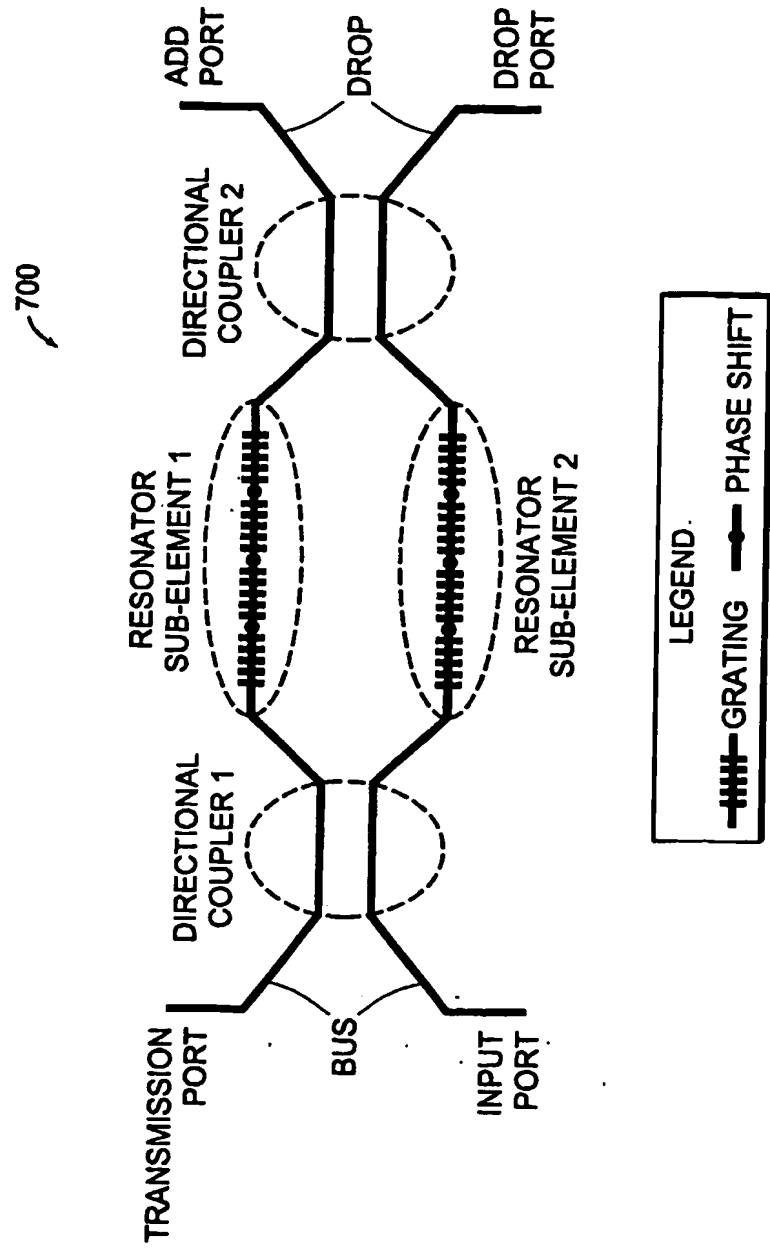


FIG. 7A

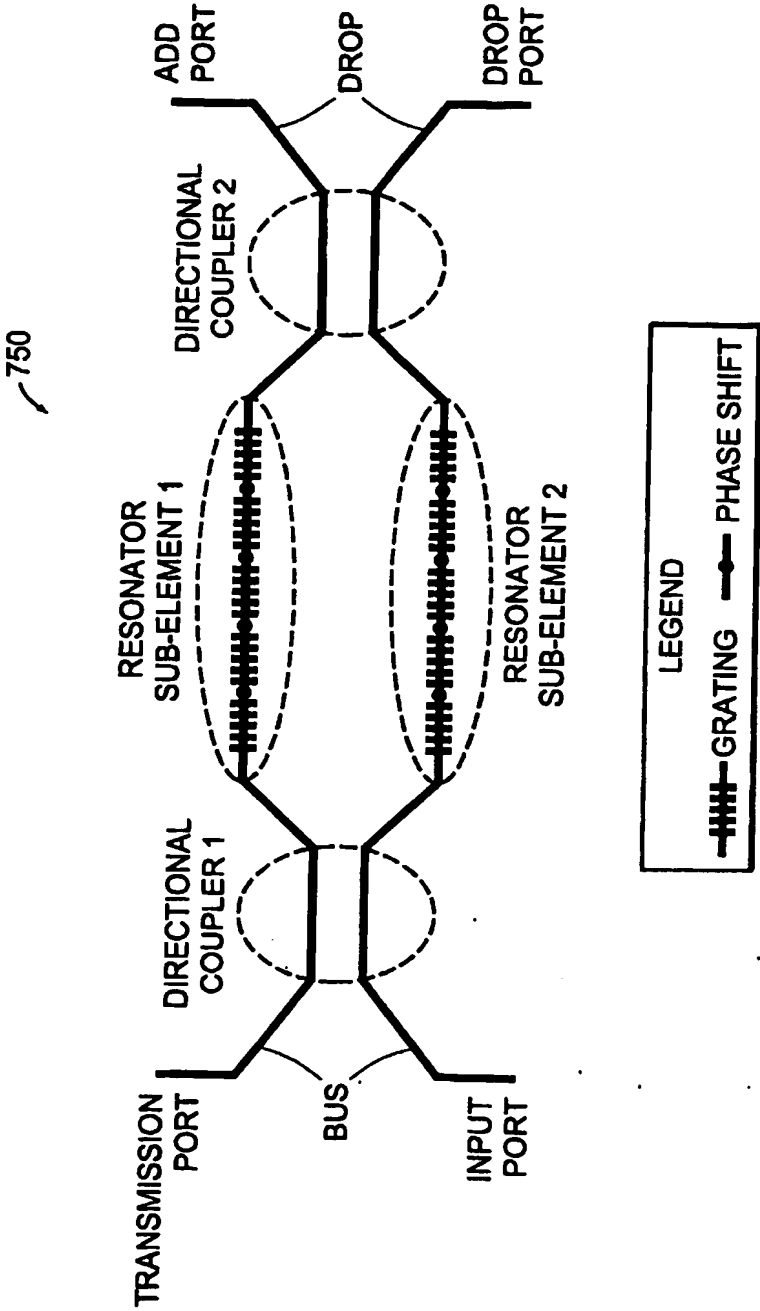


FIG. 7B

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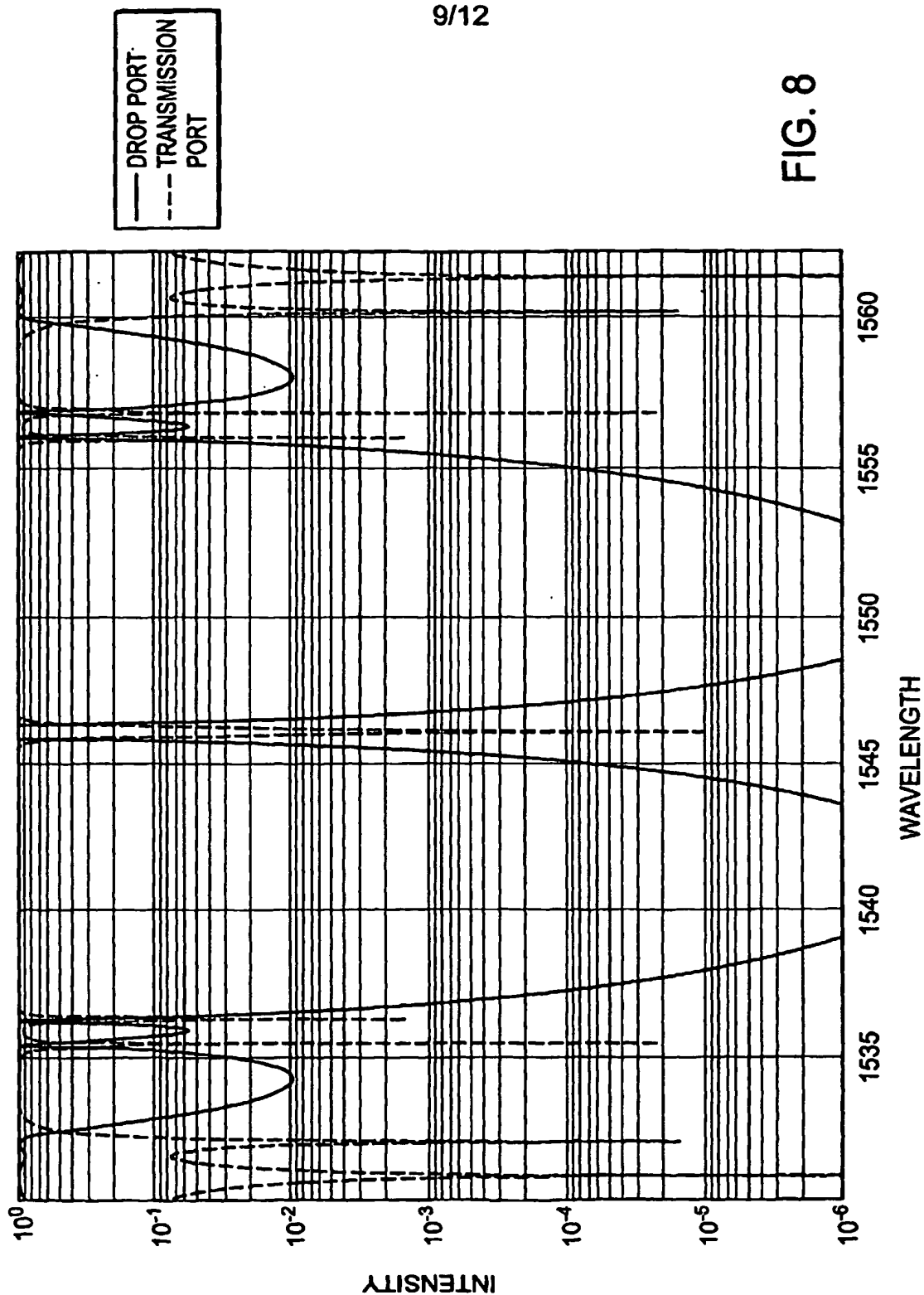


FIG. 8

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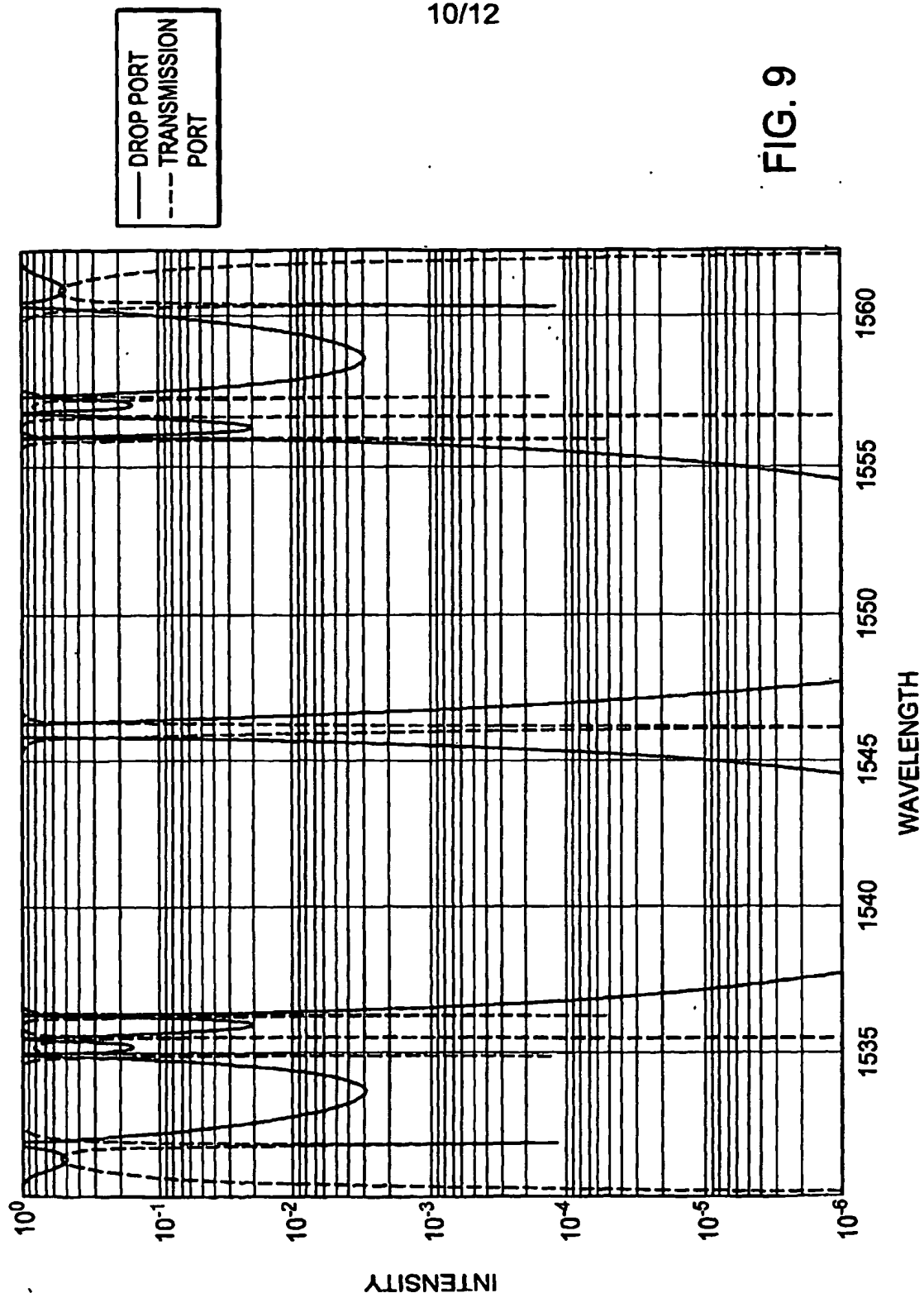


FIG. 9

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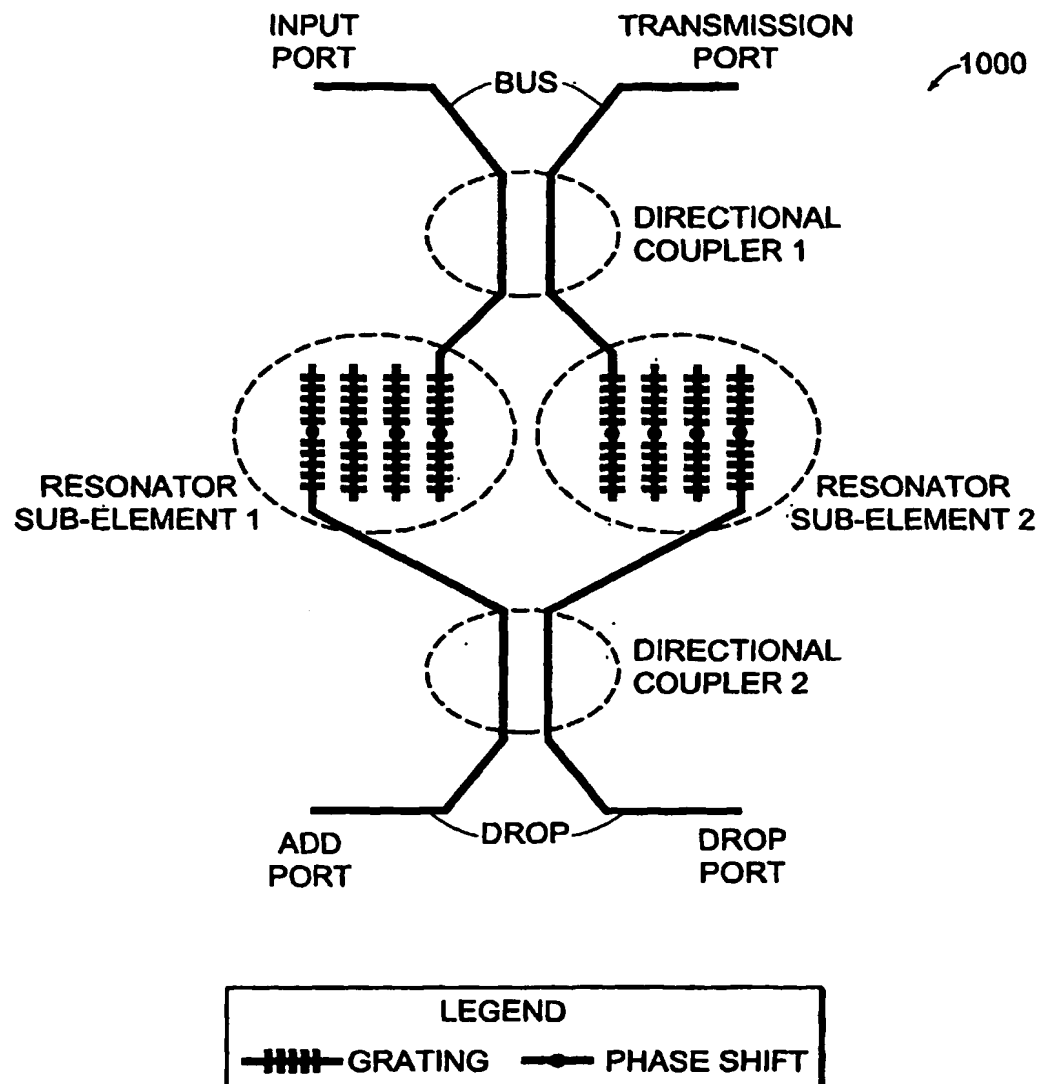


FIG. 10

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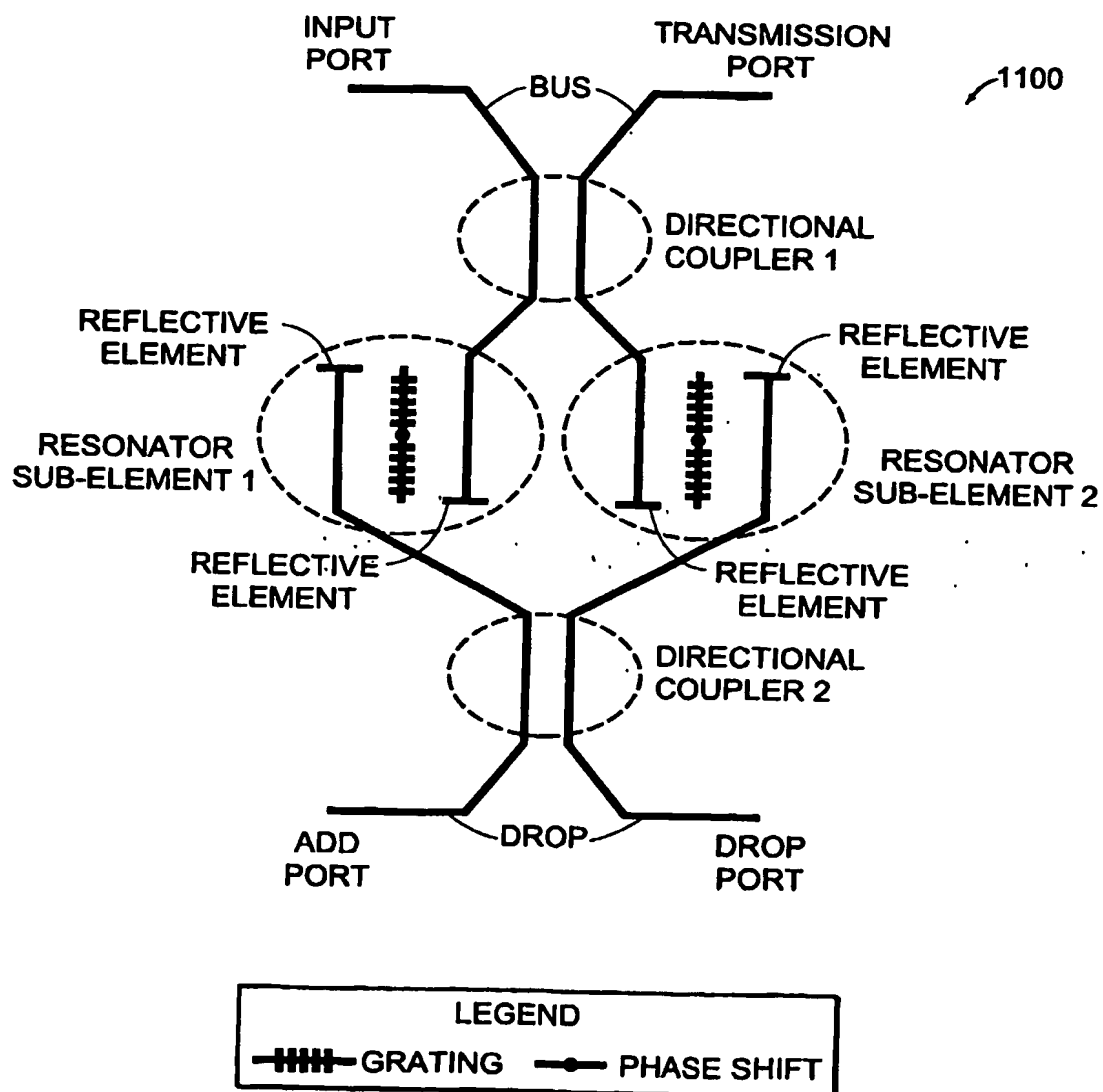


FIG. 11



## INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 03/06287

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G02F1/313 G02B6/12 G02B6/34 H04J14/02

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G02F G02B H04J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	AUGUSTSSON T: "Proposal of a phase shifted Bragg grating assisted MZI for add-drop multiplexing" IEE PROCEEDINGS-OPTOELECTRONICS, OCT.-DEC. 2001, IEE, UK, vol. 148, no. 5-6, pages 205-208, XP002246545 ISSN: 1350-2433 the whole document --- -/--	1-27

☒ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

4 July 2003

Date of mailing of the international search report

28/07/2003

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## INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 03/06287

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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